Copper Alloy SSM Casting:

A Developing Technology for Reducing the Cost of Copper Alloy Parts

November 2003

Massachussetts Office of Technical Assistance
251 Causeway Street, Ste. 900
Boston, MA 02114
617.626.1060
617.626.1095 fax
www.mass.gov/ota

DISCLAIMER

This document is designed to assist industry in analyzing the application of specific technologies. While it provides a template for the general types of questions that you should ask when evaluating a technology, it may not include all of the questions that are relevant to your business, or which your business is legally required to ask.

This document is intended to assist technology users, developers, and investors to make informed decisions about the commercial potential, process and environmental performance of specific or prospective products or processes under development. This document is not intended to communicate the full market scope or competitive position of the technology, but rather to illustrate the comparative effectiveness, or potential effectiveness, of that technology.

Acknowledgements

Authors:

Dr. Kenneth P. Young
Vforge, Inc., 5567 West 6th Ave., Lakewood, CO 80214
Tel: 303-781-0234, Ext. 203
Email: kyoung@vforge.com

Dr. Dale T. Peters
Senior Advisor
Copper Development Association, Inc.
260 Madison Ave., New York, NY 10016
Tel: 843-681-4121
Email: dtpeters@adelphia.net

This report was prepared for the Massachusetts Office of Technical Assistance (OTA), under contract no. SC-ENV-1000-3180255.

Support for this report was provided by a NICE[3] grant from the U.S. Department of Energy, Office of Industrial Technologies and administered by Dr. John S. Raschko of OTA. The experimental work on copper alloy SSM forming was funded by the world copper industry through the International Copper Association, Ltd. and managed by the Copper Development Association, Inc. Mr. Chris Rice of Vforge, Dr. Elliot Brown of E. B. Scientific, and Mr. Bill May of Purmet assisted with the experimental work at Vforge. Dr. Stephen Midson's contribution to the die material study is gratefully acknowledged. Mr. Ruedi Beck of Die Tec, GmbH, Gossau, Switzerland, provided the die tooling designs and the innovative approaches to the heated nickel-base alloy die inserts now being used in commercial production of die-cast copper rotors and for a die system at Vforge for an extended SSM production run of a brass hardware component to begin shortly.

The Massachusetts Office of Technical Assistance (OTA), a division of the Commonwealth's Executive Office of Environmental Affairs (EOEA), promotes toxics use reduction, environmental performance, health and safety, and economic competitiveness among public and private entities. Since 1990, OTA has a solid track record in working with the business community and has helped hundreds of companies in Massachusetts improve operations, cut cost in material use, and improve environmental performance. This record is a result of the vast array of industrial manufacturing expertise housed within OTA that is focused on providing non-regulatory environmental and technical support services at no cost.

Table of Contents

Introduction

Semi-Solid Metal (SSM) casting technology is a new manufacturing technology for shaped metal parts that is currently enjoying increased commercial success within the aluminum parts industry. Recent technical activity sponsored by the Copper Development Association, Inc. (CDA) and partially funded by a grant from the Department of Energy's (DOE) NICE[3] program, has provided a basis to extend the aluminum SSM technology to copper alloys. This report outlines the current state of the copper alloy SSM technology along with developments in raw material and a high temperature die system. It also provides guidelines for the successful application of copper alloy SSM casting, together with case studies showing the economic attractiveness of the technology.

It is clear from recent development efforts that semi-solid metal casting has the potential to significantly reduce production costs in a wide variety of copper alloy parts. Savings result from the net or near-net shape character of the process, high production rate, high part density and reduced rejection rate due to porosity, part weight reduction and the associated material cost savings, reduced environmental costs, and reduced machining and finishing costs. Ongoing development seeks to demonstrate the much extended die life over conventional steel dies expected from the new nickel-base alloy heated die system through production runs. Efforts to develop a "slurry-at-the-press" feedstock approach show great promise as a means to produce inexpensive SSM feedstock, however, work remains to be done in optimizing the process. Development of new copper alloys, or modifications to existing alloys, will greatly extend the range of copper alloys available for SSM casting.

Background

As much as 20% of the copper and copper alloy produced in the U.S. is used in a number of applications for its attributes such as color, corrosion resistance, machinability, formability, and galling resistance in contact with steel. These applications include builder's hardware, valves and fittings for household and commercial plumbing, fuel gas piping, compressed air systems, air conditioning and refrigeration components, electrical utility hardware, non-electrical auto and truck components, and a wide variety of other industrial machinery and equipment. Several processes are used to fabricate these parts or components of these parts, including sand and permanent mold casting, closed die forging, and machining.

Today's economy, influenced as it is by foreign competition and rising overhead, demands that parts buyers constantly find suppliers that offer both low cost and high quality. The parts manufacturer is then driven to find ways to reduce production costs to maintain a reasonable margin and stay in business. Part quality cannot be sacrificed; in fact the buyer often demands higher quality standards at no price increase. Semi-solid metal casting, i.e., die casting in the semi-solid state, offers an opportunity for economical production of high quality copper alloy parts.

Semi-Solid Metal Technology

SSM casting is a high density forming process that offers many manufacturing, productivity, and economic advantages over conventional casting or forging processes and, certainly, sand casting processes. SSM casting requires a fine grained feedstock with a special non-dendritic, spheroidal primary solid microstructure, produced by shearing or stirring the alloy in a semi-solid state or by the recently developed thermal treatment of a fine grained semi-solid dendritic microstructure. In either case, the preparation of semi-solid, non-dendritic microstructure relies upon the naturally occurring tendency for particle coarsening during the thermal transition between solid and liquid states (the semi-solid region). In the case of shear-imposing processes, this coarsening tendency is accelerated by the fluid motion imposed upon the semi-solid mass, while the strictly thermal treatments rely upon the fineness of the initial microstructure to provide sufficiently rapid particle coarsening for acceptable processing times.

Regardless of the processing route, in the semi-solid state the feedstock is rendered as a slurry of spheroidal solid particles suspended in a liquid matrix with proper rheological properties for subsequent forming operations. SSM casting technology has come to encompass the technology surrounding the formation of the semi-solid slurry and its consequent forming into a technologically useful component. For more background on SSM technology, Flemings and Young[1] discuss basic studies of rheology of semi-solid slurries and suggest processing routes for the near-net shape forming of components.

SSM casting is a technology that has only been generally available to U.S. industry for approximately 10 years following the expiration of "stranglehold patents," which kept the process strictly proprietary for much of its life until 1992-1993. As it is generally practiced today, SSM casting comprises of taking specially cast aluminum billet from a central source, cutting it to slug lengths, reheating those slugs using induction heating to the semi-solid temperature range at which it behaves as a "soft-solid" with the viscosity of modeling clay (Fig. 1), and injecting the semi-solid material into a steel die using horizontal die casting machinery.

This variation of SSM casting is often referred to as the "billet" approach. The billet approach offers prescribed chemistry and cleanliness control that can be specific to the feedstock source and a process environment much closer to wrought processing than casting. Since it generally uses widely available cold chamber horizontal die casting machines as the casting unit, SSM casting has the potential for widespread use and application by existing casters equipped with such machines. More than 6,000 horizontal cold chamber machines are installed in North America, with an estimated casting capacity of

Figure 1: 3 inch diameter aluminum alloy 357 semi-solid slug being sliced by a knife at 50% solid/50% liquid. This SSM material has the consistency of modeling clay.

approximately 4 million metric tons of aluminum alloys.

SSM Casting Benefits Using the Billet Approach

As an innovative process, SSM casting offers great potential to save costs, save energy, and reduce the environmental impact of casting by eliminating or reducing the handling of liquid metal within the SSM manufacturing cell.

SSM forming of aluminum alloys differ from other casting processes in that rather than using fully liquid metal as a feed material, it uses a semi-solid slurry in billet form that is typically 50% solid-50% liquid. Once produced, this semi-solid slurry, which is handled as though it is a solid billet, is transferred to a high-pressure casting machine and formed using reusable dies. The manageable viscosity allows control of slurry flow during the forming operation to minimize turbulence, thus significantly reducing air and oxide entrapment that is deleterious to mechanical performance. The casting temperatures of SSM slurries are significantly reduced relative to conventional casting, which employs superheated alloys, and more importantly, the heat content of the material can be much less (up to 50% less).

From the viewpoint of the SSM plant operator, the partial melting required eliminates excess energy consumption typical within "foundry" operations, as well as significant liquid metal handling issues. Partial melting alone has the potential to reduce "melting energy" by as much as 30%. The aluminum alloy bar stock purchased by the plant for SSM casting bears the cost of melting and the magneto-hydrodynamic (MHD) stirring during continuous casting to generate the critical microstructure.

Casting SSM material also reduces the thermal load on dies and offers increased productivity due to a shorter cooling cycle. As the part solidifies, pressure is applied to aid in the feed of solidification shrinkage. By minimization of porosity and defects in this manner, components with excellent mechanical and functional performance can be produced.

SSM casting has also demonstrated improved casting yield and reduced scrap relative to other casting and shaping processes, reduced metal consumption in the manufacture of 3-dimensional shapes due to near-net shaping, reduced metal losses relative to liquid metal processing due to much reduced oxidation and dross losses and, specifically for aluminum alloys, reduced energy for heat-treatment via improved low temperature T5 aging. In addition, since the alloy is only partially melted within the SSM casting system, productivity can increase due to faster solidification times and reduced die stabilization times after casting ejection.

As a consequence of the improved thermal management inherent in SSM casting, the potential to improve cast-part tolerance control is another less obvious advantage of the technology. All these factors provide a significant opportunity to improve the competitiveness of the U.S. casting industry in both aluminum, and now copper alloy, parts production.

In summary, readily apparent advantages of SSM casting are:

- Net or near-net shape processing.
- Reduced temperature of the feedstock compared to the casting of a fully liquid material, which makes for less thermal fatigue heat, less mold or die wear, and less solidification shrinkage.
- Potential for improved tolerance control relative to other processes due to the inherently tight process temperature control associated with SSM casting and reduced thermal cycling of dies.
- Control of viscosity that can result in less turbulent mold and die filling, which minimizes gas entrainment, porosity, shrinkage, hot tearing, and other solidification defects.
- Lower shear strengths of semi-solid slurries that are associated with lower forming forces than corresponding operations for solid metal, such as forging.
- Finer, more uniform, microstructures leading to higher mechanical performance.
- Improved material utilization in forming small components due to productivity and accurate introduction of metal into the forming dies.
- Increased casting speed relative to liquid processing due to lower thermal demands on the dies.

SSM Aluminum Casting Experience and Cost Factors

Since 1992, SSM cast aluminum has seen growth both within North America and elsewhere around the world, primarily as a result of weight reduction efforts within the transportation industry. Today approximately 60 SSM casting cells operate on four continents, consuming roughly 30 million pounds of aluminum alloy feedstock. Despite the clear technical advantages over other casting processes, however, the conversion of other casting processes or alternative manufacturing techniques to SSM casting has been slower than anticipated, primarily due to economic factors centered around the premium cost of specially cast SSM feedstock.

Recently, as a consequence of the high SSM raw material premiums charged by the primary suppliers (which can exceed 35% of the raw alloy cost) and because many advantages of SSM casting are now generally recognized, development efforts in SSM casting have focused upon techniques and processes to eliminate the need to purchase primary grade, specially cast SSM feedstock. UBE, a Japanese manufacturer of casting equipment, is leading the development efforts in SSM casting to eliminate the need to purchase primary grade, specially cast SSM feedstock by generating semi-solid slurry, or so-called “virtual slugs”, produced from such slurry, directly within the casting cell from conventionally melted liquid alloy. These current efforts seek to mitigate the economic disadvantages of SSM. The “slurry-based” SSM caster must purchase only ingot or scrap such that raw material cost remains on par with alternative casting processes. However, in striving for this economic improvement, these “slurry on demand” approaches return liquid metal processing to the casting cell. Die casters in general, as opposed to plants devoted solely to the billet approach of aluminum alloy SSM casting, are equipped to melt and handle molten metal and are comfortable with these operations. Slurry on demand technology requires local chemistry and melt cleanliness control, is sensitive to turbulence during the process, and represents a unique casting event each cycle.

SSM Casting of Copper Alloys

The higher melting ranges of copper alloys have, until this time, presented both formidable issues and opportunities. Key to the successful implementation of SSM copper alloy casting is the availability of suitable die materials able to withstand the severe operating conditions associated with casting at temperatures greater than 800ºC (1500-1800ºF). This challenge appears to be resolved, however, as die materials and techniques of operation capable of withstanding repeated cycling at copper alloy SSM temperatures have recently been identified as part of the development of the copper motor rotor (described below).

In addition, the higher operating temperatures also facilitate more rapid cool-down in the die, therefore promoting faster casting cycles than are achievable with aluminum alloys.

Copper Alloy Cost Factors

Two factors are critical for SSM casting of copper alloys to be economically competitive with certain other processes: 1) the cost of die amortization due to deterioration of dies in casting alloys with high melting temperatures and 2) the cost of the starting stock.

As explained above, aluminum SSM casting costs-to-date are primarily driven by the cost of raw material, since standard die steels with adequate life that are already used for aluminum alloy die casting are easily adapted to SSM casting. In the case of copper alloys, however, die casting is very limited primarily as a result of inadequate die life. Whereas typical aluminum dies built from H-13 steel might reasonably be expected to survive 150,000 to 200,000 cycles, it is not uncommon for copper alloy dies to last less than 10,000 to 20,000 cycles. CDA experience in die casting electrical grade copper was that severe heat checking was seen in less than 20 shots. Since H-13 or similar steel (or nickel alloy) dies require many hours of machining and EDM (electro-discharge machining) time, the sunk cost of an SSM die might range from \$20,000 to greater than \$100,000. At a die life of less than 20,000 cycles it becomes readily apparent that die life is a major cost factor in copper alloy casting, overshadowing even the cost of raw material.

Raw material costs for copper alloy SSM casting are expected to exhibit the same trend seen for SSM aluminum alloy parts, where about 30% of the cost of a part is associated with the feedstock. For example, cost estimates have shown that a 350 gram double shift fork produced in a four cavity die by the Strain Induced Melt Activation (SIMA) process from extruded and cold drawn C64200 alloy feedstock is 29% more expensive than if the alloy were to be melted at the press and MHD processed to the SSM billet on a continuous batch basis (“slurry-at-the-press”). Calculation showed the same savings for a 350 gram brass hardware part made from C37700 bar stock in a four cavity die compared to an estimate for the slurry-at-the-press case. Clearly a versatile, low cost, on-site process for production of SSM feedstock capable of competing in many market segments with commercial alloys is required.

The next several sections address these critical cost drivers and briefly review some of the recent development work to solve these problems.

Development of a High Temperature Die System

Recently, an effort sponsored by the Copper Development Association (CDA), in collaboration with Trex Enterprises and OTA, and partially funded by U.S. DOE’s NICE[3] program, resulted in the very successful application of improved die materials and heating to the die casting of high conductivity (pure) copper motor rotors[2, 3]. Pressure die casting is the only practical manufacturing method for the large production levels of integral horsepower motor rotors. This development, recently adapted and commercialized by SEW Eurodrive in Germany for production of a broad range of motors, is briefly reviewed here.

The Copper Motor Rotor Project involved the use of tungsten and molybdenum refractory alloys, as well as nickel-based alloys, as die inserts and pre-heating the die to temperatures in excess of 600º C to reduce thermal fatigue of the die to acceptable levels during casting of the rotors. Classical issues of oxidation and contamination of the copper were not observed, which facilitate sound process economics. Also, the lack of contamination from shot sleeves or die materials facilitate scrap recovery.

During the Copper Motor Rotor Project, thermal modeling of the die casting process performed for high conductivity copper and stainless steel showed that the thermal responses of the die for these two cast materials were within approximately 1% of each other. Furthermore, modeling indicated lower die surface temperatures and temperature gradients in the die for casting of copper alloys. Long die-life-in-service has been successfully demonstrated with high-conductivity copper in test dies (over 1,000 shots without deterioration) and for copper motor rotors (approximately 200 shots to date showing good die-life). Based on the results of thermal modeling and the experimental work on pure copper described above, it is anticipated that less severe thermal conditions and lower die preheat temperatures will be required with SSM cast copper alloys, indicating probable success for this technology. In addition, the similarity in thermal response between copper and stainless steel bodes well for the application of SSM technology to ferrous alloys.

The best practices developed from the Copper Motor Rotor Project for the successful pressure die casting of copper motor rotors are summarized below:

- The high melting temperature of copper (1083°C) requires the use of high temperature, high performance die materials. Conventional die steels such as H-13 lose strength rapidly at the operating temperature that is well above the tempering temperature. High temperature materials found suitable for dies include the tungsten alloy Anviloy 1200, as well as the solid solution strengthened nickel-base alloy INCONEL alloy 617. INCONEL alloy 625 is also promising. Although not tested in the CDA program, HAYNES alloy 230 should also be excellent in this application. This alloy is more weldable than alloy 617 and has somewhat higher elevated temperature strength. Alloy 230 was used in the first commercial production dies for copper rotors.
- To obtain extended die life and avoid premature failure by thermal fatigue of the surface, it is essential when die casting pure copper to preheat and to operate the dies at temperatures in the range of about 625 to 650ºC. The higher die temperature reduces the surface-to-interior ΔT on each shot, which in turn greatly minimizes the expansion and contraction associated with each cycle and the thermal fatigue of the surface that leads to crazing and cracking. A schematic diagram of the tooling for the horizontal pressure die casting of copper motor rotors, showing heater locations and insulation placement in and behind the die inserts, is shown in Figure 2.
- Use of shot-by-shot induction melting of copper is a practical and advantageous

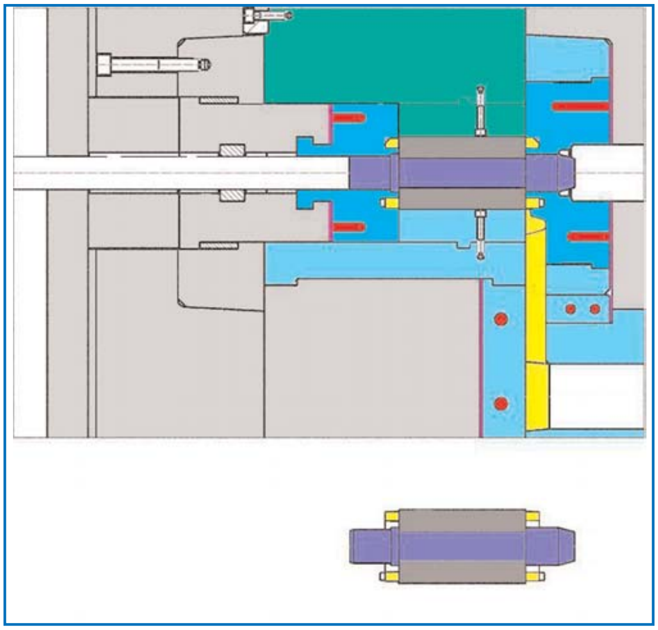
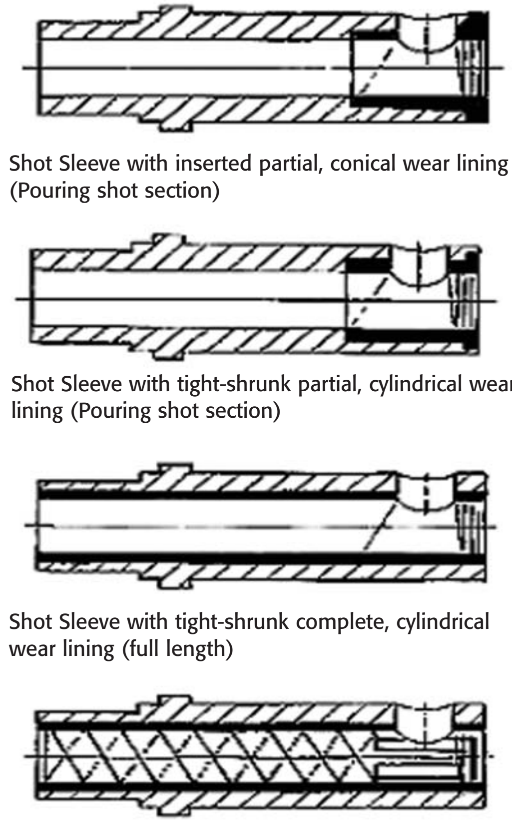


Figure 2: Horizontal pressure die caster with tooling for rotor casting in closed position. The arbor (dark blue) and the steel rotor laminations (dark gray) are shown in the detail beneath and in position in the machine. Copper from the shot sleeve biscuit, runner, and end rings are shown in yellow. The nickel alloy end ring inserts are shown in medium blue with electrical resistance heater elements in red. These are backed with insulation (pink), as are the runner inserts that would be nickel alloy or tungsten. Red circles here indicate heater positions. The movable slide to allow insertion and removal of the rotor is shown in green. Ordinary steel backing plates of the master mold set are shown in light gray. (Courtesy of DieTec, GmbH)

alternative to gas fired melting in a large volume furnace, as is the practice for aluminum. Melting the copper one shot at a time greatly minimizes exposure of the molten copper to air and the resulting oxygen pick up. Dipping from a large furnace and transfer of molten copper to the shot sleeve is much more problematic with the high melting metal as compared to the same operations with aluminum. An enclosed and inert gas pressurized melting system fed through a seal with copper wire rod from a continuous coil has proved to be an ingenious and practical melting system. The inert gas (nitrogen) protects the molten copper from oxidation. Similar to equipment used in low pressure die casting of copper alloys, a controlled pour directly to the shot sleeve of the die casting machine is done by increasing the pressure to force molten copper out a tube, of which the lower end is below the bath surface. This system was built for copper rotor production in Germany.

- A heated shot sleeve surrounded by a thermal wrap is very helpful in maintaining sufficient heat in the molten copper charge to ensure complete filling of the rotor cavity and in reducing thermal fatigue. A replaceable center insert at the point of pour into the shot sleeve allows for convenient replacement of this high wear area. DieTec designs for replaceable shot sleeve inserts are shown in Figure 3. Use of INCONEL alloy 617or HAYNES alloy 230 for the shot sleeve may be very helpful in production. (The machine used in the test program was equipped with steel shot sleeves).



Shot Sleeve with inserted partial, conical wear lining (Pouring shot section)

Shot Sleeve with tight-shrunk partial, cylindrical wear lining (Pouring shot section)

Shot Sleeve with tight-shrunk complete, cylindrical wear lining (full length)

Shot Sleeve with tight-shrunk complete, cylindrical wear lining (full length) and inserted cooling system

Figure 3: Designs for shot sleeves with replaceable inserts. (Courtesy of DieTec, GmbH)

Sources of equipment, die materials and design, and copper alloy materials for copper alloy SSM casting are listed in Appendices I and II.

Copper Alloy SSM Casting Experience

Limited trials and some limited production of SSM cast copper alloy parts have occurred on and off over the past 20 years. Until this time, however, the restricted die life obtained with typical H-13, or even H-20, die steels has limited the application of the technology.

In the early to mid-1980's the ITT Corporation, via its Engineered Metal Processes Division and other associated divisions, manufactured production quantities of approximately 20 different parts. Later, AMAX Inc., the subsequent holder of the MIT patents, also attempted to manufacture copper alloy SSM cast parts. Short die life, however, resulted in these efforts being economically infeasible, despite good casting quality.

Figure 4: 400-ton SSM casting cell at Vforge, Inc.

As an extension of the CDA/NICE[3] Copper Motor Rotor Project, Vforge, Inc. of Lakewood, Colorado is working under contract to the CDA to apply the high temperature nickel alloy die technology to the SSM forming of copper alloys. At this time, the project awaits delivery of the first high temperature nickel alloy die that will be used in this work.

Vforge Copper Alloy Casting Trials

In 2001 and 2002, Vforge worked on the development of copper alloy SSM raw material technology and basic SSM casting parameters using steel die technology. A number of copper alloy parts were produced from three primary alloys: copper alloy C37700 (copper-zinc), copper alloy C64200 (aluminum-silicon bronze), and copper alloy C90500 (tin bronze).

Example parts using these alloys are described below. To date, Vforge has used only the Strain Induced Melt Activation (SIMA) "billet" approach described below for producing parts, since it represents a process route using readily available raw material.

SIMA is a feedstock approach developed by ITT Corporation in the 1980's, where a previously deformed bar stock is heated into the semi-solid state prior to forming[4]. During heating, as the solidus temperature is approached, the microstructure recrystallizes to an equiaxed grain structure and melting occurs at the grain boundaries to produce an SSM microstructure of spheroidal solid particles in a liquid matrix. A wide variety of alloys can be SSM formed with this approach, and cold drawn bar for a number of alloys is readily available. However, this is an expensive approach and is generally confined to small parts formable from billets cut from bar no larger than about 1.5 in. (36 mm). For the purposes of CDA's development efforts, SIMA was considered a means for obtaining immediate experience with SSM of selected copper alloys, but it is not deemed to be an economically viable alternative for ultimate feedstock development, except for very special situations involving small parts that can be produced from small diameter rod stock.

Vforge's experience to date confirms that standard horizontal cold chamber die casting machines are adequate for SSM casting of copper alloys and that the induction heating systems currently employed for aluminum alloys can be used for copper alloys with minimal modifications. Vforge has used a 400-ton IdraPrince machine (Fig. 4) to cast SIMA-processed copper alloy slugs ranging in diameter from 1 inch to 2.5 inches. While copper alloy SSM casting uses higher injection velocities than typical for aluminum alloy SSM, they are still much lower (20-60 inches per second) than the injection velocities used in high pressure die casting.

At Vforge, the copper alloy slugs were re-heated on a 100 kW SSM induction heating system using 8 coils arranged in a standard carousel system (Fig. 5). As is typical for induction heating, the efficiency of heating is a close function of the "fill percentage" of the work piece to the coil, such that

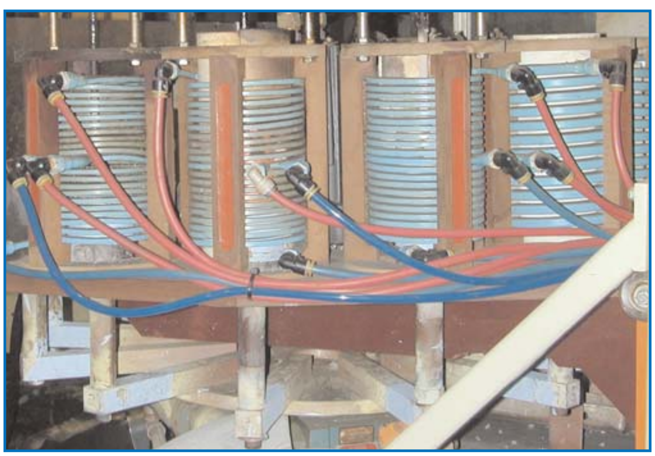


Figure 5: IHS-Inductoheat 100 kW induction heating carousel.

coil geometry and work piece geometry are closely matched while still allowing flexibility in slug size. The Vforge coil system was adapted by IHS-Inductoheat to allow electrical connections or "taps" at various coil heights to facilitate optimum fill percentage at a variety of slug sizes. A SIMA copper alloy slug is shown ready to cast in Figure 6.

An obsolete brake caliper shape was chosen as a test die since it is representative of a complex

Figure 6: SIMA copper alloy slug ready for casting.

geometry and provided the challenge of filling around a main core (Figs. 7 & 8).

Two factors combine to make the SIMA method inherently expensive; the size limitation on bar stock and the premium, or fabrication, charge

Figure 7: SIMA slug and complete shot of brake caliper test part.

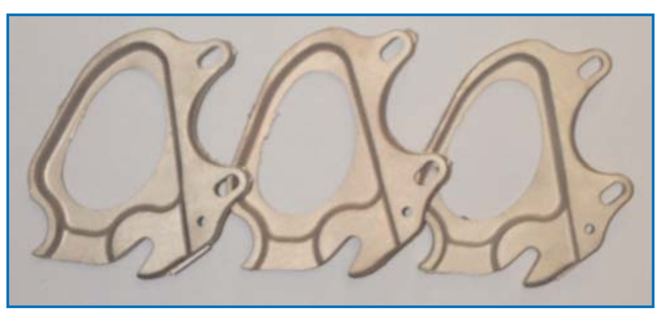


Figure 8: Brake caliper test parts used at Vforge Inc. Copper alloys C64200, C90500 and C37700, left to right.

for bar stock over the raw material cost. The productivity of the die casting machine and its tooling are important factors in the part cost equation. Therefore, die casters use multi-cavity dies to hold costs down. When multi-cavity dies are used, the small size of SIMA starting stock limits the economical application of the method to parts

Figure 9: Golf club sole plate SSM cast from copper alloy C64200.

weighing only a few ounces with an allowance for the runner and biscuit weight. These generally approach the total part weight. This contributes to high costs because the parts must bear the premium over raw material for the extruded and cold drawn bar stock, only about half of which is sold as SSM machine cast parts. The premium, which includes fabrication cost and profit margin, of copper alloy bar stock is at least equal to the raw material cost.

An example of a successful application of the SIMA method is the golf club sole plate shown in Figure 9. Approximately 100,000 of these plates were SSM cast in the mid-1990's using cold drawn copper alloy C64200 bar stock as the starting material, which replaced the hot stamped and machined copper alloy C37700 yellow brass. The C64200 is a silicon aluminum bronze and is considerably harder and more durable in this application.

Copper Alloy SSM Raw Materials Development

The crux of efforts to develop an SSM casting technology for copper alloys is the development of a robust and economical feedstock. In this regard, previous experience in feedstock development for the mature aluminum alloy SSM casting industry was noted. Magnetohydrodynamically (MHD) stirred, continuously cast aluminum alloy SSM feedstock, although high in quality, represents an expensive approach that significantly adds to the overhead in producing aluminum alloy parts via SSM. Approximately 30% of the cost of an SSM aluminum alloy part is associated with feedstock. Obviously, a more economical feedstock would result in a more cost effective and competitive manufacturing process.

SSM Starting Stock via Grain Refinement

Initial CDA work at Vforge on raw material development examined the concepts of "passive" production using grain refinement. In this method, a cast starting product with a fine grained equiaxed dendritic microstructure is produced by adding a grain refiner to the melt. A typical SSM microstructure of globular solid particles in a liquid matrix is formed during heating into the semi-solid state when dendrites coarsen and spheroidize. This SSM feedstock approach is successfully employed in the production of aluminum alloy feedstock[5] and was investigated at Vforge for application to brass SSM forming. Several types of melt additives, some containing iron with and without boron, and others containing zirconium, magnesium, iron and phosphorous, either as binary or multi-component alloys, are used to grain refine brasses. Generally, these additives are effective in grain refining some yellow brasses but are ineffective for copper-rich alloys. Process control, in terms of fade and remelting of scrap, are issues. Melt inoculation did not always give reliable results, even in the yellow brasses, and it is not possible to recognize the degree of success achieved until after the material is cast. For these reasons, the grain refinement approach to copper alloy feedstock production was abandoned.

Batch MHD-Stirring Slurry-at-the Press

Recently at Vforge, the development of a rheocasting, “slurry-at-the-press” feedstock approach to SSM was successful. In developing a slurry-at-the-press technology, an MHD-stirring approach was pursued using aluminum alloy 357 (the most common SSM aluminum alloy) as a preliminary model system, given the lower solidus temperature and extensive experience with SSM casting of this alloy. Following the initial work on aluminum alloy 357, formable microstructures were produced by batch MHD-stirring of yellow brass and a tin bronze (copper alloy C90500). The work using aluminum alloy 357 and copper alloy C90500 is described below.

- *Aluminum alloy 357* is a hypoeutectic nominally Al-7Si-0.5Mg alloy. In the semi-solid state the microstructure is comprised of primary α solid particles and liquid that subsequently transforms via a eutectic reaction. Shearing in the semi-solid state results in non-dendritic, spheroidal primary α.
- *Copper alloy C90500* is a nominally Cu-10 w/0 Sn -2 w/0 Zn alloy. A Cu -10 w/0 Sn binary alloy was deemed an appropriate prototype alloy to consider microstructural evolution during rheocasting and SSM casting because of its wide freezing range of approximately 180 ºC.

For both the aluminum and copper alloys, small “one-shot” batches of slurry were MHD-stirred in stainless steel crucibles and then allowed to freeze quiescently for prescribed times and power to generate an SSM slug. The batches of aluminum alloy 357 weighed 3 to 4 pounds, and those of the copper alloy C90500 weighed approximately 7 pounds. The SSM slugs were successfully reheated using induction heaters and formed in heated dies, demonstrating the viability of the rheocast feedstock/SSM casting approach to manufacturing on a pilot scale.

For the initial testing, an MHD-stirring apparatus was constructed from the stator of an electric motor of sufficient size (Fig. 10). A stainless steel crucible (Fig.11) with liquid metal was transferred to the bore of the stator and allowed to

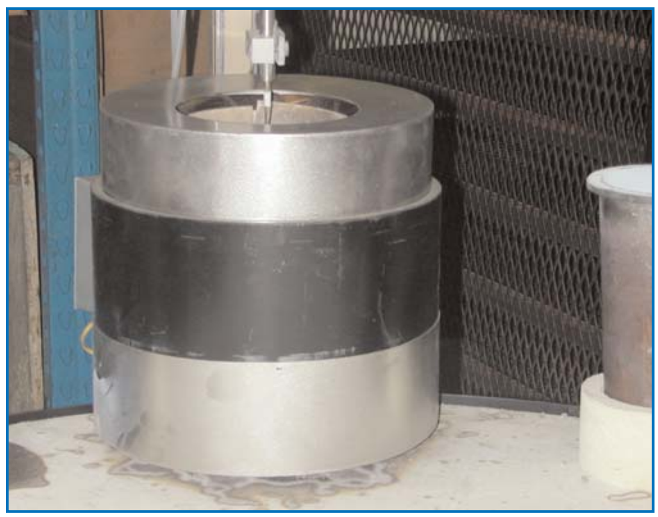


Figure 10: Experimental electromagnetic stirrer used for batch slurry tests.

Figure 11: "Slurry-at-the-press" carousel was used for later casting trials with containment crucibles and electromagnetic stirrer from batch tests.

cool into the semi-solid state while being stirred with the magnetic field developed in the bore of the stator.

Results Using Aluminum Alloy 357

Feedstock billets were produced by fully melting alloy 357 at 685ºC and transferring material to stir crucibles at 640ºC. At 620ºC the crucibles were lowered into the stator for continuous stirring as the material cooled to a given temperature, at which point the crucibles were withdrawn from the stirring chamber and allowed to cool. Then, the fully solidified billets were each machined to 2.5 in. diameter x 3 in. length.

These machined slugs were subsequently formed using the Vforge 400-ton press and brake caliper die set. Billet induction heating was accomplished with the heater set at 2.74 volts and a 42 sec cycle on 8 stations. The part forming temperature was approximately determined with a hand-held thermocouple.

For comparison, production MHD concast billet possesses a fine equiaxed solidification grain structure and a good SSM microstructure, with globular primary α and entrapped liquid. Some of the primary particles possess a rosette morphology. The batch MHD-stirred billet possesses a microstructure comparable to that of the MHD concast production material, except it possesses a significantly coarser primary solid particle size. To place the effect of MHD-stirring in perspective, reheated billet that is not stirred is characterized by a coarse, sometimes columnar, solidification grain structure and a coarse dendritic microstructure.

Parts could be successfully SSM cast from batch MHD-stirred billet. The primary particle size in all parts formed from batch MHD-stirred material is significantly coarser than parts formed from the concast MHD billet, consistent with the microstructural results described above. However, there is a tendency for liquid to segregate in the part and solidification shrinkage porosity to form in the vicinity of the gate.

Results for Copper Alloy C90500

The copper alloy C90500 feedstock billets were produced in the same general manner as the aluminum alloy 357 billets, by fully liquefying alloy stock at 1175ºC and rapidly transferring the metal to stir crucibles at 1020-1040ºC. At this point the stir crucibles were lowered into the stator for continuous stirring as the material cooled to between 980 and 990ºC. The billets were then each machined to 2.5 in. diameter x 3 in. length.

Again, these machined slugs were subsequently formed using the 400-ton press and the brake caliper die set. Billet induction heating was accomplished manually at a single station with the heater set at 3.25 volts and various heating times. The part forming temperature was approximately determined with a hand-held thermocouple. The formed part with runner bar and biscuit is shown in Figure 12. (The part after trimming is also shown as the center part in Figure 8.)

Figure 12: SSM-cast copper alloy C90500 CAAD4 part with runner bar and biscuit.

The microstructure of the billet MHD-stirred to 985ºC is shown in Figure 13. A globular rosette primary solid morphology is generally observed but some of the primary particles still possess a remnant of the dendritic morphology. The primary solid particles have a mean size of 114 microns.

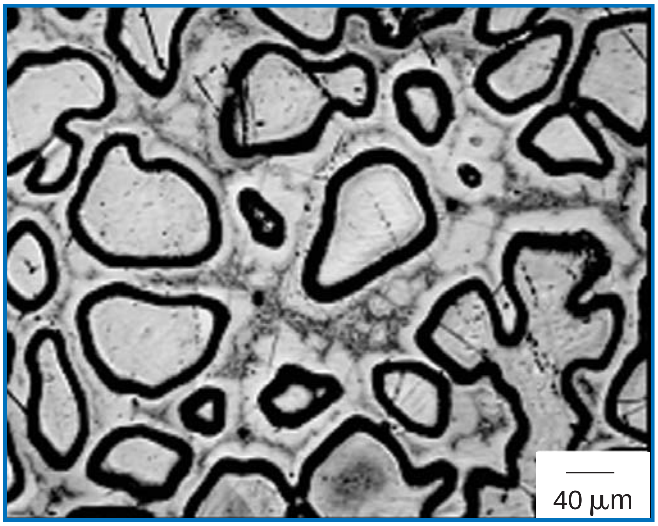


Figure 13: Microstructure of copper alloy C90500 billet MHD-stirred to 985°C.

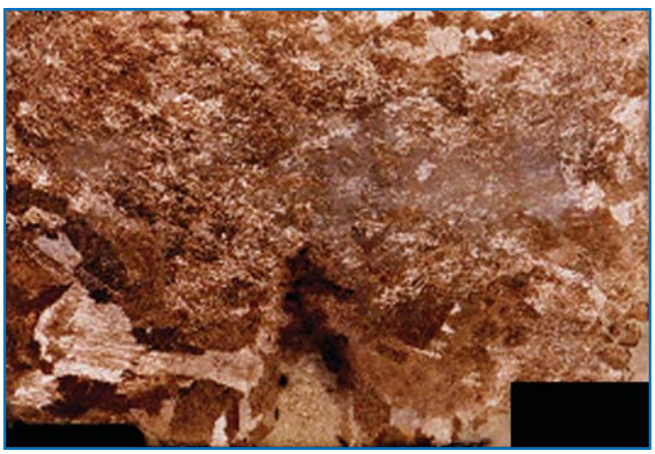


Figure 14: Macrostructure of unstirred copper alloy C90500.

Billet material that was reheated but not stirred is characterized by a coarse solidification grain structure. The primary solid in unstirred material is mostly dendritic in morphology. The dendrite arm spacing ranges approximately from 50 to 70 mm. The macrostructure is shown in Figure 14 and the microstructure in Figure 15.

Specimens cut from biscuits or parts formed from MHD-stirred billets all exhibited equiaxed

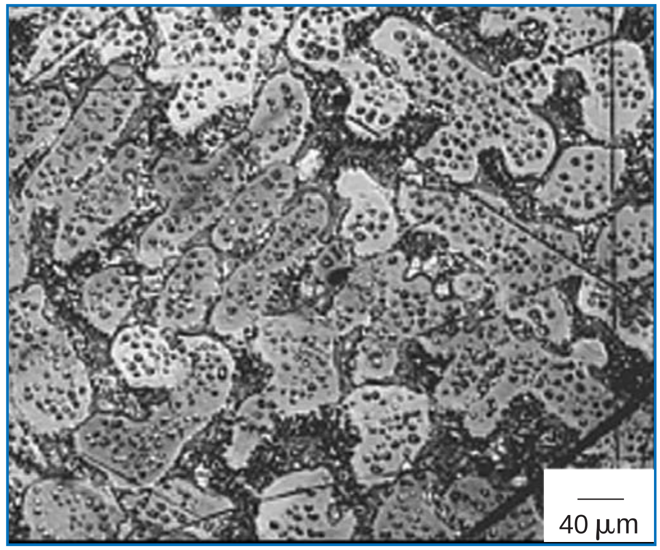


Figure 15: Microstructure of unstirred copper alloy C90500.

solidification grain structures much finer than the biscuit structures for billets with no stirring. Thus, there is a significantly distinguishable effect of stirring on structure. This structure is reflected in the much lower viscosity and reduced forming pressures required for the MHD-stirred billets. Sections from the part opposite and removed from the gate showed a fine equiaxed solidification grain structure with only minor porosity (Fig. 16). The microstructure is shown in Figure 17.

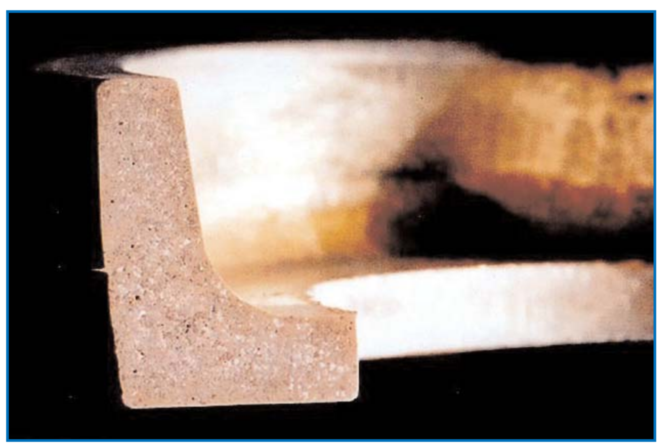


Figure 16: Cross-section of brake caliper test casting opposite to gate SSM cast from MHD-stirred copper alloy C90500.

Although copper alloy C90500 parts can be successfully SSM cast from batch MHD-stirred billet, as was the case for the aluminum alloy 357 parts, there is a tendency for liquid to be squeezed out of the biscuit and runner, and segregate in the part, and also for solidification shrinkage porosity to form in the vicinity of the gate. A higher shear rate during stirring would aid in the formation of more spheroidal primary α with less entrapped liquid associated with particle coalescence. This would result in less liquid segregation and shrinkage porosity during SSM casting, and is an area for future development work.

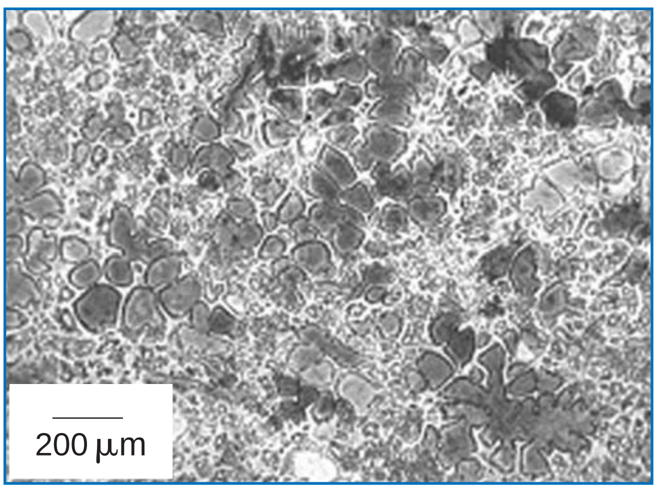


Figure 17: Microstructure of a copper alloy C90500 SSM-cast part.

High magnification images of the structure shown in Figure 15 indicate that, due to similarity in microstructure to the prior liquid regions, the multiphase circular features observed in primary dendrites and primary globular rosettes are actually globules of liquid. The liquid globules in the primary phase appear to be the result of a liquid entrapment process associated with coarsening by coalescence. The primary particle boundary becomes unstable, forming a dendritic shape. During coarsening, as the particle boundary moves out into the liquid, globules are pinched off and entrapped in the primary solid.

Cost estimates indicate that MHD-stirred copper alloy billet can be produced on a continuous batch basis for $0.15/lb over raw material cost. Billets weighing several pounds can be produced. This factor, combined with reduced die amortization costs by virtue of the high temperature die system described above, enables SSM casting of copper alloys to be competitive with certain other processes.

Environmental Advantages of Copper Alloy SSM Casting

In the case of the red and semi-red cast copper alloys, SSM casting offers significant environmental advantages by removing lead from the environment. Most of the common copper casting alloys contain significant amounts of lead, which reduces cost and improves pressure tightness and machinability. For these alloys the dominant casting process in use today is sand casting. Unfortunately, during the casting process, the sand used has a tendency to absorb lead, making it a hazardous waste for copper alloy casting foundries. This poses a significant environmental problem, demanding the control of air emissions and either sand reclamation and/or its eventual disposal, the costs of which must be included in the selling price of the sand-cast part. SSM casting of these copper alloys using high temperature nickel alloy dies is not burdened by these environmental concerns and associated costs. Moreover, the lead content of these alloys can be reduced to a low level sufficient for good machinability (about 1.5%), since machining requirements are reduced through net-shape casting. This will also ameliorate the hot shortness problem and holds promise in allowing red brasses to be machine cast. Finally, reduced lead levels are very important in the significant portion of red and semi-red sand castings that are used in potable water systems in terms of meeting EPA's drinking water standard for lead.

Case Studies of SSM-Cast Copper Alloy Parts

A number of examples are available demonstrating that SSM casting of small copper alloy parts offers substantial cost savings (approximately 35 to 55%) over the conventional production method, even when the more expensive SIMA starting stock and conventional steel dies were used. The cost data presented here were obtained in the late-1980's, predating the concept of slurry-at-the-press starting stock. While material and operation costs may have changed, the cost savings realizable by using SSM casting (expressed as a percentage of the conventionally produced part cost) are believed to be valid and probably conservative estimates for today.

Sand Cast Parts

The first two examples are sand cast parts converted to SSM casting. Foundries today are under immense pressure to reduce the environmental impacts of their operations, including air emissions and the disposal of sand contaminated with metals and organic binders. With these factors in mind, it is likely that the cost of the part as a sand casting would be higher when today's environmental costs are included. SSM cast parts, on the other hand, will be free of these environmental costs. In addition, today's SSM casting costs will benefit from the much improved die life now obtainable using the heated nickel-base alloy die technology. An estimate of this additional savings is included.

Split Bolt

Sand Cast

This piece of electric utility pole line hardware (Fig. 18) was sand cast for many years in copper alloy C95600, a silicon aluminum bronze with the nominal composition Cu - 7%Al - 3%Si. At the time of this cost comparison, the finished part cost was $1.89 per piece including material, foundry, and machining costs.

SSM Cast

The part produced by SSM casting was made in the equivalent wrought alloy, C64200, purchased as cold drawn rod. The rod was cut into slugs of essentially the same part weight, 0.34 lbs. With the semi-solid tooling used, the entire billet was formed into the part with almost zero runner and biscuit to be removed.

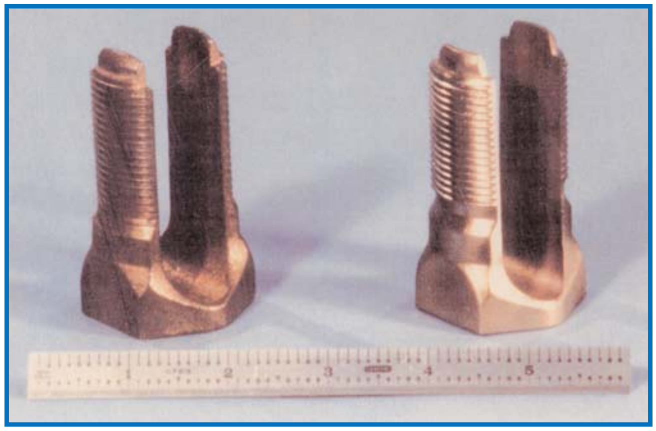


Figure 18: Split bolt pole line hardware. C95600 sand casting, left; SSM formed in C64200, right.

The process formed the part to final shape with no machining required. The SSM cost breakdown was as follows:

Purchased Material	$0.68
Forming	0.33
Die Amortization	0.16
Total Costs	**$1.17**

This represents a 38% savings using the SSM casting process compared to sand casting. The die amortization cost could well be reduced by a factor of ten with the availability of the new die technology. This would increase the cost savings to 45%.

Water Pump Housing

Sand Cast

This pump housing (Fig. 19) was sand cast in the semi-red brass casting alloy C84400, nominal composition Cu - 3%Sn - 9%Zn - 7%Pb. The lead content assures pressure tightness and facilitates the machining operations.

SSM Cast

The starting stock for the SIMA process was the yellow brass forging alloy C37700, Cu -38%Zn – 2%Pb, purchased as readily available extruded and cold drawn rod. The high density and absence of porosity, characteristic of SSM cast parts, enabled the wall thickness to be reduced resulting in a significant reduction in casting weight (Table 1) and material cost. In addition to the elimination of lead contaminated foundry sands, the lower lead content of the SSM cast part also represents reduced contamination of the water through the pump. The costs of the sand cast and SSM cast parts are compared in Table 2.

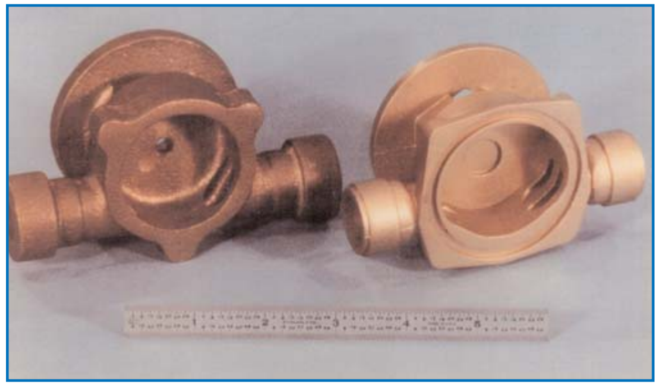


Figure 19 : Water Pump Housing - C84400 Sand casting, left; SSM formed in C37700, right.

Table 1: Weight (lbs) of Sand Cast and SSM Cast Water Pump Housings

Water Pump Housings	Sand Cast	SSM Cast
Weight, As-Cast, lbs	1.66	0.87
Weight, Machined, lbs	1.07	Not Available

Table 2: Cost Comparison of Sand Cast and SSM Cast Water Pump Housings

Water Pump Housings Cost Data	Sand Cast	SSM Cast
Cast Part, Including Material	$3.03	N/A
Purchased Material	N/A	$0.85
Forging	N/A	$0.40
Machining/Finishing	$2.45	$1.20
Tooling	N/A	$0.48
TOTAL	**$5.48**	**$2.93**

N/A: not applicable

The cost saving here is 46% using SSM casting compared to sand casting. Again, longer die life by a factor of ten is expected, and extends the cost saving to 54%.

Closed Die Forged Parts

Two parts produced by closed die forging were also analyzed. The material used in both processes is yellow brass C37700 forging rod. For the SSM process, the rod is in the half hard condition.

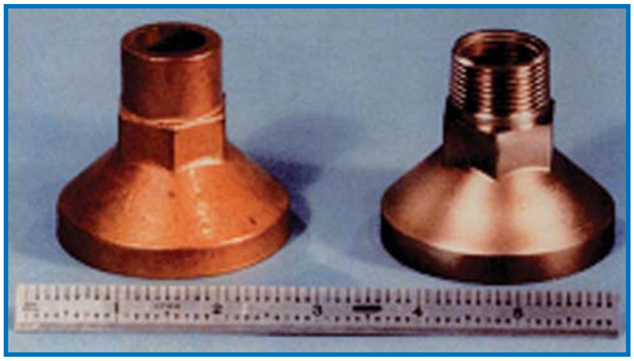


Figure 20: Nipple, C37700 Brass. Closed Die Forged on left; SSM Cast, right.

Figure 21: Cap, C37700 Brass. Close Die forged, left. SSM Cast, right.

Nipple

Table 3: Weight of Closed Die Forged and SSM Cast Nipples

Nipple	Closed Die Forged	SSM Cast
Weight Forged, lbs	0.50	0.27
Weight Machined, lbs	0.32	Not Available

Table 4: Cost Comparison of Closed Die Forged and SSM Cast Nipples

Nipple Cost Data	Closed Die Forged	SSM Cast
Forged Part, Including Material	$0.86	N/A
Purchased Material	N/A	$0.23
Forging	N/A	$0.33
Machining/Finishing	$0.32	$0.10
Tooling	N/A	$0.12
TOTAL	**$1.18**	**$0.78**

N/A: not applicable

The cost saving in this example is 34%. Assuming tooling costs to be reduced by a factor of ten increases this cost saving to 43%.

Cap

Table 5: Weight of Closed Die Forged and SSM Cast Cap

Cap	Closed Die Forged	SSM Cast
Weight Forged, lbs	0.40	0.19
Weight Machined, lbs	0.35	0.18

Table 6: Cost Comparison of Closed Die Forged and SSM Cast Cap

Cap Cost Data	Closed Die Forged	SSM Cast
Purchased Part, Inc. Material	$0.83	N/A
Purchased Material	N/A	$0.16
Forging	N/A	$0.13
Machining/Finishing	$0.20	$0.18
Tooling	N/A	$0.11
TOTAL COSTS	**$1.03**	**$0.68**

N/A: not applicable

The reduced part weight and less machining cost for the SSM cast part result in a 34% cost saving, which is extended to 45% with the projected increase in die life now possible with the new technology.

References

1. M.C. Flemings and K.P. Young, “Rheocasting”, Yearbook of Science and Technology, McGraw-Hill, New York, 1978.

2. D.T. Peters, J.G. Cowie, E.F. Brush, Jr. and S.P. Midson, “Use of High Temperature Die Materials and Hot Dies for High Pressure Die Casting Pure Copper and Copper Alloys”, Proceedings of the North American Die Casting Association Die Casting Congress, Rosemont, IL, 2002.

3. D.T. Peters, J.G. Cowie, E.F. Brush, Jr., and S.P. Midson, “Advances in Pressure Die Casting of Electrical Grade Copper”, American Foundry Society 106th Casting Congress, Kansas City, MO, Paper No. 02-002, 2002.

4. E. Tzimas, A. Zavaliangos and A. Lawley, “The Effect of Microstructure on the Rheological Response of Alloys in Semi-Solid: A Comparison of MHD, SIMA, and Spray Cast Alloys,” 5th International Conference on Semi-Solid Processing of Alloys and Composites, A.K. Bhasin, J.J. Moore, K.P. Young and S.P. Midson, Eds., Colorado School of Mines, Golden Colorado, 1998.

5. S.C. Bergsma, US Patent No. 5,571,346, Nov. 5, 1996.

Contacts

For more information or for discussion of potential cost savings using SSM casting of a particular copper alloy part, contact the following people:

MA Office of Technical Assistance
251 Causeway Street, Suite 900
Boston, MA 02114

Tel: 617-626-1060
Email: maota@state.ma.us

Dr. John G. Cowie
Copper Development Association, Inc.
260 Madison Avenue
New York, NY 10016

Tel: 212-251-7202
Email: jcowie@cda.copper.org

Vforge, Inc. is working with CDA on copper alloy SSM process development, and offers production capability for SSM cast copper alloy parts.

Dr. Kenneth P. Young
Vforge, Inc.
5567 West 6th Avenue
Lakewood, CO 80214

Tel: 303-781-0234, Ext. 203
Email: kyoung@vforge.com

Appendix I

Sources of Equipment, Die Design, and Die Materials

Die Design:

DieTec GmbH
Mr. Ruedi Beck
Bedastrasse 39 CH 9200 Gossau
Switzerland
Tel: +41 (0)71 388 20 30
Fax: +41 (0)71 388 20 31
Email: info@dietec.ch

Die Casting Machines:

Bühler Druckguss AG
1100 Xenium Lane
P.O. Box 9497
Plymouth, Minnesota 55441
Minneapolis, MN 55440
Tel: 763-847-9900
Fax: 763-847-9911

IdraPrince Corporation
670 Windcrest Drive
Holland, Michigan 49423
Tel: 616-394-8248
Fax: 616-394-1250
www.idraprince.com

High Temperature Insulation:

Brandenburger Liner GmbH & Co.
Taubensihlstrasse 6
D-76829 Landau
Germany
Tel: +49 6341 5104-30
Fax: +49 6341 5104-55
Web: www.Brandenburger.de

Thermal Ceramics
P.O. Box 923
Augusta, GA 30903-0923
Toll Free: 800-526-9665

Induction Heating Equipment:

IHS-Inductoheat, Inc.
5009 Rondo Drive
Fort Worth, Texas 76106
Tel: 817-625-5577
Fax: 817-625-1872
Toll Free: 800-486-5577

High Temperature Materials:

Anviloy:
The Mallory Corporation
P.O. Box 59
Augusta, NJ 07822-0059
Tel: 973-579-6132
Fax: 973-579-5231

Haynes 617, 625, or 230:
Carpenter Technology
P.O. Box 14662
Reading, PA 19612-4662
Toll Free: 800-338-4592
Tel: 610-208-2000
Fax: 610-208-2361

Haynes 617, 625, or 230:
Haynes International Inc.
1020 West Park Avenue
Kokomo, IN 46904-9013
Tel: 765-456-8031
Fax: 765-456-8175
Contact: Mr. H. Lee Flower
Tel: 765-456-6253

INCONEL alloys 617 or 625:
Special Metals Corporation
3200 Riverside Drive
Huntington, WV 25705-1771
Tel: 304-526-5100
Toll Free: 800-334-8351

Appendix II

Copper Alloy Sources

Ingot:

Atlas Pacific Corporation
P.O. Box 726
Colton, CA 92324-0726
Phone: 909-421-1200
Fax: 909-421-0618
Email: AtlasPac@aol.com

California Metal-X
366 E. 58th Street
Los Angeles, CA 90011
Phone: 323-234-9281
Fax: 323-234-0812
Email: tfstrelitz@cmxmetals.com

Colonial Metals Co.
P.O. Box 311
Columbia, PA 17512-0311
Phone: 717-684-2311
Fax: 717-684-0602
Email: mmann@colonialmetalsco.com

The Federal Metal Co.
7250 Division Street
Bedford, OH 44146
Phone: 440-232-8700
Fax: 440-232-8726
Email: dnagusky@federalmetal.com

The G. A. Avril Company
4445 Kings Run Drive
Cincinnati, OH 45232
Phone: 513-641-0566
Fax: 513-641-0568
Email: johnavril@fuse.net

H. Kramer & Co.
1343 West 21st Street
Chicago, IL 60608
Phone: 312-226-6600
Fax: 312-236-4713
Email: chapmanh@hkramer.com

I. Schumann & Co.
22500 Alexander Road
Bedford, OH 44146
Phone: 440-439-2300
Fax: 440-232-2988
Email: dschumann@ischumann.com

Ingot Metal Co. Ltd.
111 Fenmar Drive
Weston, Ontario
M9L 1M3 Canada
Phone: 416-749-1372
Fax: 416-749-1371
Email: ivan@ingot.ca

National Metals Co.
P.O. Box 102
Leeds, AL 35094
Phone: 205-749-8110
Fax: 205-699-6767
Email: aewnmi@msn.com

River Recycling Industries, Inc.
4195 Bradley Road
Cleveland, OH 44109
Phone: 216-749-8110
Fax: 216-749-8107
Email: jgrodin@rivershell.com

Sipi Metals Corp.
1720 N. Elston Avenue
Chicago, IL 60622-1579
Phone: 773-276-0070
Fax: 773-276-7014
Email: rjb@sipimetals.com

W. J. Bullock, Inc.
P.O. Box 539
Fairfield, AL 35064
Phone: 205-788-6586
Fax: 205-788-5714
Email: WJBullock@aol.com

Extruded and Drawn Rod/Bar:

Ansonia Copper & Brass, Inc.
(Ansonia Plant)
P.O. Box 109
75 Liberty Street
Ansonia, CT 06401
Phone: 203-732-6600
Toll Free: 800-521-1703
Fax: 203-735-3787
Web: www.ansoniacb.com

Cerro Metal Products Co.
Bellefonte Works
P.O. Box 388
Bellefonte, PA 16823
Phone: 814-355-6217
Fax: 814-355-6227

Chase Brass & Copper Company
(Olin Corporation)
P.O. Box 152
Route 15
Montpelier, OH 43543
Phone: 419-485-3193
Fax: 419-485-5949
Web: www.chasebrass.com

Chicago Extruded Metals Co.
1601 South 54th Avenue
Cicero, IL 60650
Phone: 708-656-7900
Toll Free: 800-323-8102
Fax: 708-780-3479
Web: www.cxm.com

Extruded Metals, Inc.
302 Ashfield
Belding, MI 48809
Phone: 616-794-1200
Toll Free: 800-428-7296
Fax: 616-794-1386
Web: www.extrudedmetals.com

Mueller Brass Company
2199 Lapeer Avenue
Port Huron, MI 48060
Phone: 810-987-7770
Fax: 810-987-9108
Email: Rod: mlee@muellerindustries.com